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THE BAUSCHINGER EFFECT IN COPPER AND COPPER-ZINC ALLOYS

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THE BAUSCHINGER EFFECT IN COPPER AND COPPER-ZINC ALLOYS

ABSTRACT

A series of five different copper-zinc polycrystalline alloys, ranging from commercially pure copper to 65% Cu 35% Zn brass, were strained various amounts up to 5% in tension and reverse strained in compression. The Bauschinger strain is shown to be dependent on composition. An equation relating plastic strain and the Bauschinger effect is presented and experimentally verified. Preliminary data shows that the Bauschinger strain is dependent on grain size for the 65% Cu 35% Zn alloy, but is independent of grain size for the OFHC copper.

Cross-Reference Data

Brass Alloys

Bauschinger Effect

Plastic Strain

Overstrain

Grain Size

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FIGURES

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INTRODUCTION

One of the interesting aspects associated with the study of the plastic flow of metals is that known as the Bauschinger Effect (BE). This causes the material to become anisotropic with respect to the direction of loading after the metal has been plastically strained. Although the BE has been known for a long time, only a relatively small amount of work has been reported in an attempt to clarify the phenomenon. One of the explanations of this behavior is based on back stresses resulting from dislocation pile-ups[1-3].

Woolley studied a series of fcc and bcc polycrystalline alloys and concluded that the BE was independent of grain size and slightly dependent on purity and temperature[4]. Buckley and Entwistle[5] studied high purity aluminum single crystals and compared their results to polycrystalline specimens. They concluded that strain hardening and the BE are intimately related. Hence, one could conclude that the mechanisms contributing to strain hardening strongly influence the magnitude of the BE.

There appears to be only a small amount of literature concerning the effect of alloying in solid solution type alloys on the BE[3,6]. Consequently, it was felt that a study of a series of alloys of a given system, with emphasis on work hardening during prestrain and the effect of grain size, would give additional insight into the factors contributing to the BE.

THEORY

Following an expression presented by Conrad[7], we can write that

$$\epsilon_{pl} = C_1 \rho b S \qquad (1)$$

where ϵ_{pl} is the plastic strain, C_1 is a constant, ρ is the density of dislocations, b is the Burger's vector, and S is the distance the dislocations move during the deformation.

By combining this equation with an expression given by McClintock[8]

$$\epsilon_{\beta} \approx \rho^{\frac{1}{2}} b \qquad (2)$$

and eliminating ρ, we can obtain an expression for the Bauschinger strain ϵ_{β} in terms of the plastic strain

$$\epsilon_{\beta} = A\left(\frac{\epsilon_{pl}}{S b}\right)^{\frac{1}{2}} \qquad (3)$$

where A is a constant.

EXPERIMENTAL PROCEDURE

A system of Cu-Zn alloys was selected for this particular investigation because the alloying effect of zinc into copper is quite well known from the standpoint of the stress-strain behavior[9]. Commercially pure OFHC copper and copper-zinc alloys having nominal compositions of 5, 10, 20, and 35 wt. % zinc were utilized. Tensile-compression specimens were machined from 1.25 inch diameter rods to the configuration shown in Fig. 1, with the exception of the 5% Zn material which was swaged to 7/8 inch diameter and annealed to give a grain size equal to

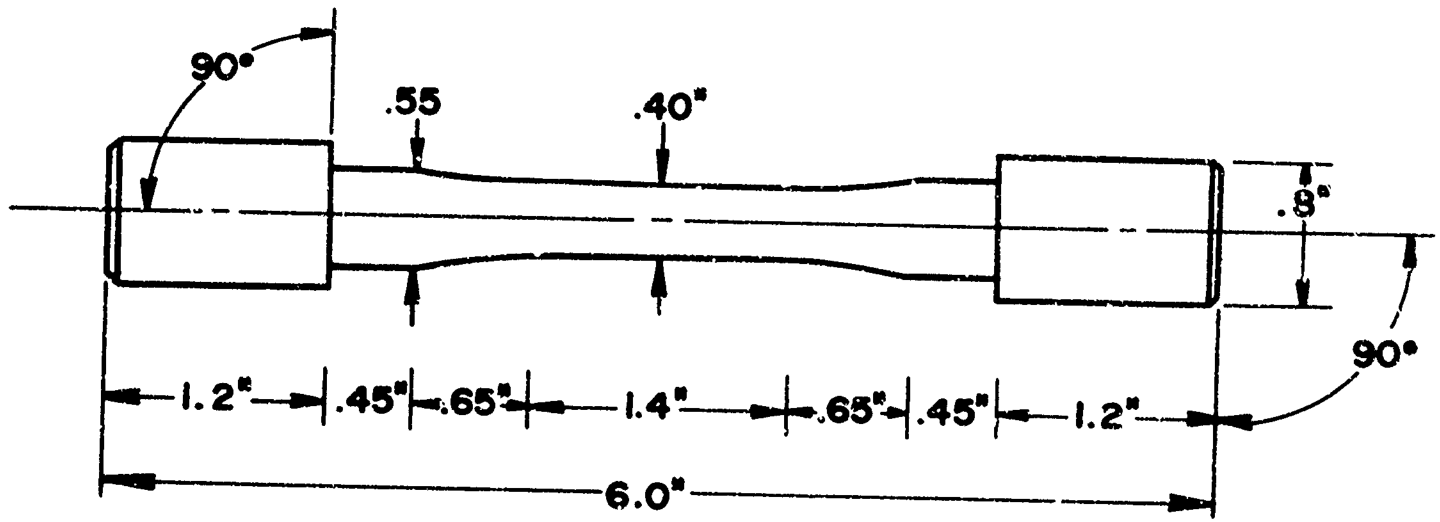

Figure 1. Sketch of Specimen Configuration

the other alloys. Tables I and II give a summary of the heat treatments and the grain sizes resulting therefrom as determined by the linear intercept method. The pure copper was annealed for 3 hours at 1000°F before machining and the copper and brass specimens were all annealed at 500°F for 3 hours in Argon after machining to eliminate machining residuals.

A closed-loop electro-hydraulic servo-controlled testing machine was used to test the specimens and to control the mechanical straining at a constant nominal strain rate of 10^{-4} in/in/sec. Details pertaining to the measurement of load and strain have been previously reported[10-11].

EXPERIMENTAL RESULTS AND DISCUSSION

Because of the large amount of strain hardening in compression after previous tensile overstraining beyond 2-3 percent, it was not advisable to use a ratio of yield stresses to define the magnitude of the BE. Therefore, the method used here for quantitatively defining the BE is essentially the same as outlined by Woolley[4]. The Bauschinger Strain (ϵ_β) is measured as the difference in the absolute value of the strains between the tensile and compressive half cycles at a given percentage of the maximum flow stress in the tensile half cycle. Figure 2 illustrates the definition.

From observing the experimental data, we can see that the strain hardening exponent n is functionally related to the alloy composition. This is shown in Fig. 3 which is a semi-log plot of strain hardening exponent vs. percent zinc content in copper.

Table I. Composition and Grain Size for Alloys Studied

Composition Wt.% Cu	Wt.% Zn	Alloy Designation	Grain Size (ASTM Equiv.)
100	0	A	6.0
95	5	B	6.5
90	10	C	6.5
80	20	D	6.0
65	35	E	6.0

All specimens stress relief annealed at 500°F for three hours after machining.

Table II. Grain Size Heat Treatments for Alloys Studied

Composition Wt.% Cu	Wt.% Zn	Heat Treatment	Grain Size (ASTM Equiv.)
100	0	*1000°C 5 Hrs. - AC	2.5
100	0	As Received	6.0
100	0	*400°C 24 Hrs. - AC	10.0
65	35	*750°C 5 Hrs. - AC	1.0
65	35	As Received	6.0
65	35	*450°C 24 Hrs. - AC	9.0

*Grain size anneal after 50% reduction in area from cold swaging.

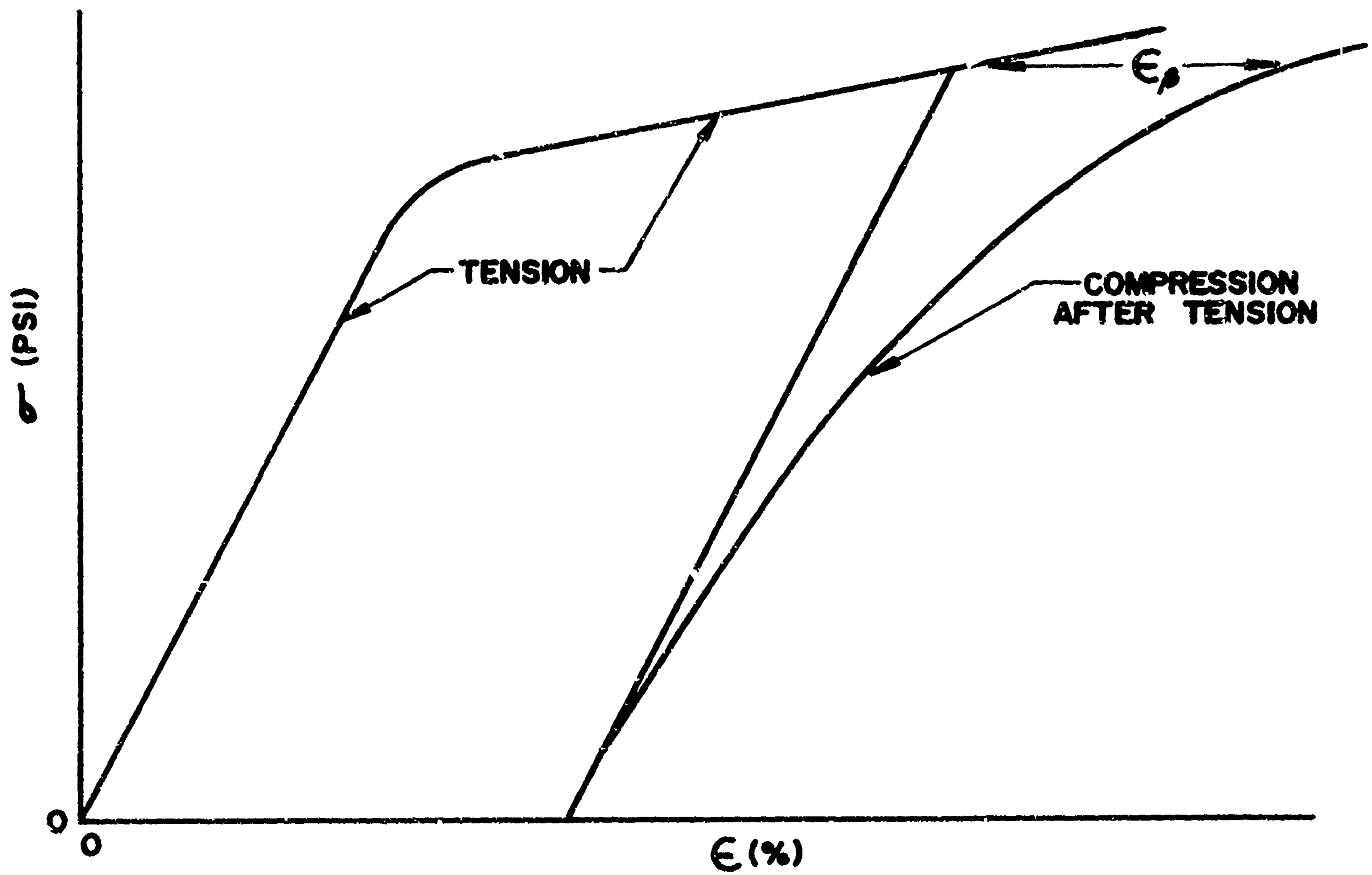

Figure 2. Schematic Stress-Strain Diagram Showing the Bauschinger Strain (ϵ_β) Definition

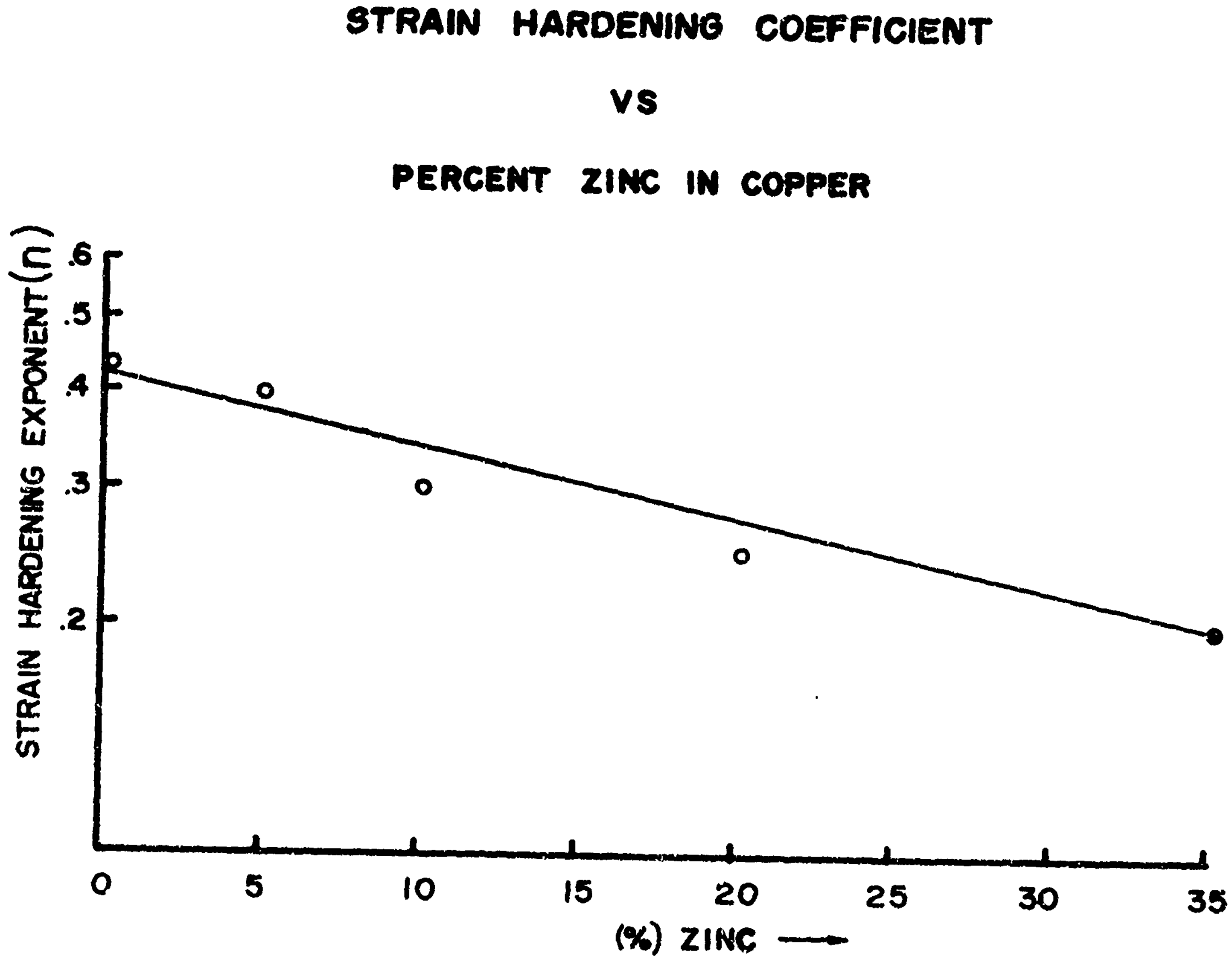

Figure 3. Semi-Log Plot of n vs. % Zinc in Copper

Figure 4 shows a graph of Bauschinger strain vs. total uniaxial strain in tension for the five different alloys studied. This shows that there is a systematic increase of the BE with increasing zinc content. Since the tensile elastic strains up to plastic yielding are quite small compared to the plastic strains, we can assume, with little error, that the total strain equals the plastic strain.

Figure 5 is constructed from Fig. 4 and shows the Bauschinger strain (ϵ_β) vs. $\epsilon_{pl}^{\frac{1}{2}}$ for the five different alloys. Assuming that S equals the grain size, which in this case is constant, and b varies only by 2-3 percent over the range from pure copper to 65/35 brass,[12] we may then write equation (3) as

$$\epsilon_\beta = \alpha_A \epsilon_{pl}^{\frac{1}{2}} \tag{3A}$$

α_A from equation (3A) is the slope of these curves and is a non-dimensional parameter dependent on the alloy composition. The range of α_A is from .21 for the pure copper to .50 for the 65/35 brass. This plot verifies the form of equation (3) and shows that ϵ_β depends on the half power of the plastic strain for this particular alloy system.

Figure 6 is a plot of the strain hardening exponent n vs. α_A. This shows a definite correlation between strain hardening, plastic strain and the BE.

Figures 7a and 7b show a plot of ϵ_β vs. total strain for three different grain sizes of pure copper and 65/35 brass. The most important thing brought out by these graphs is that the Bauschinger

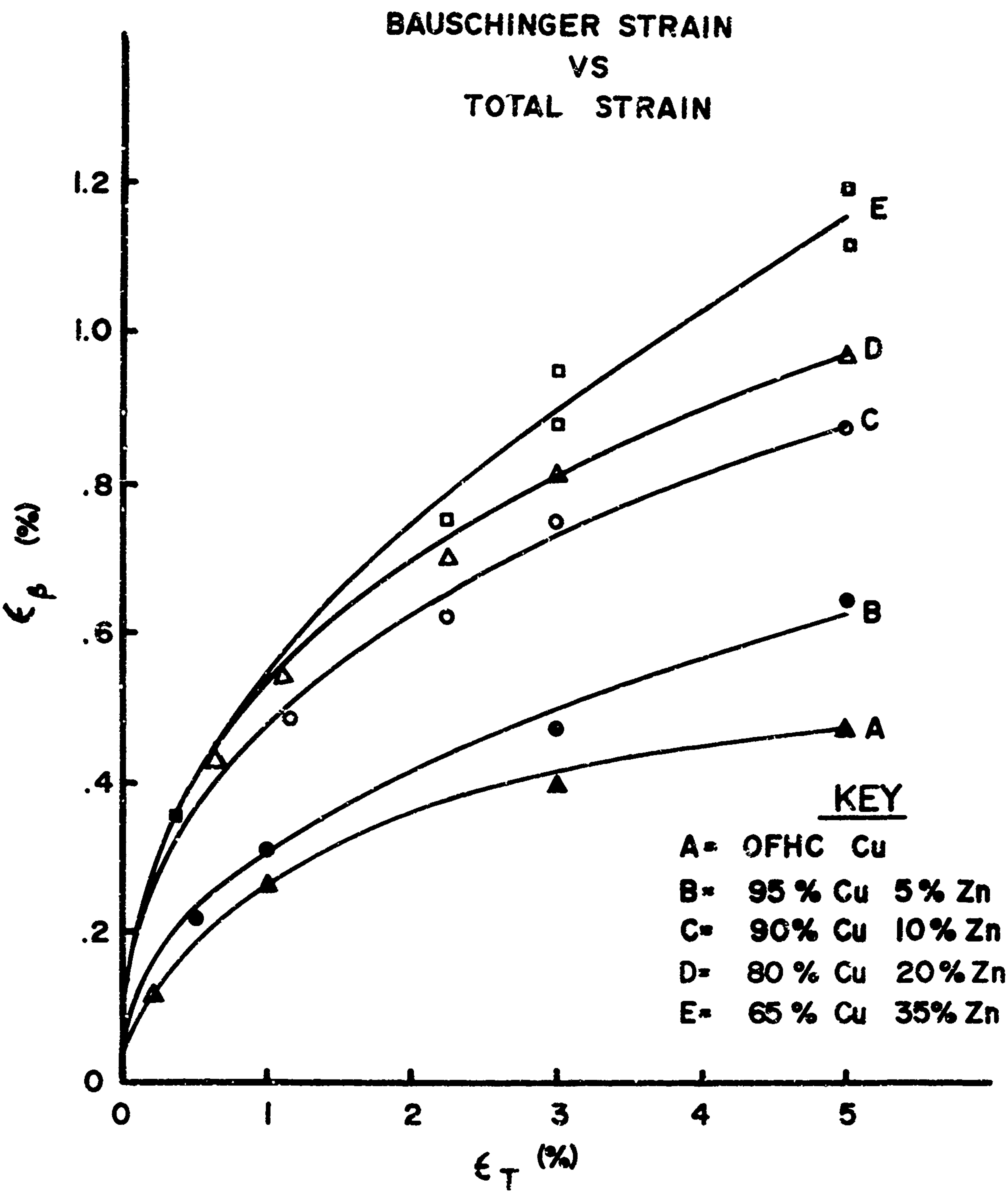

Figure 4. ϵ_β vs. ϵ_{total}

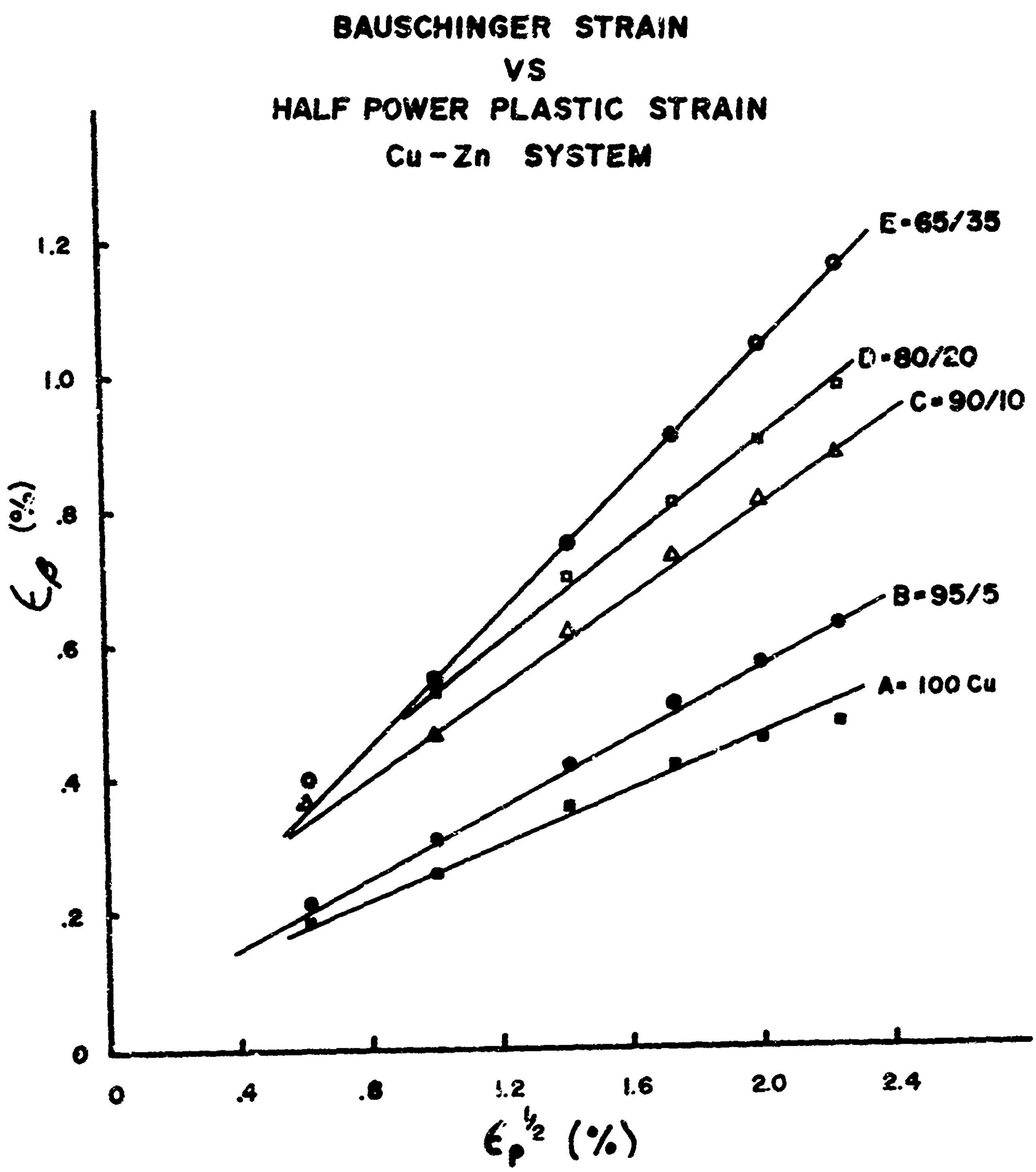

Figure 5. ϵ_β vs. $\epsilon_{pl}^{\frac{1}{2}}$

STRAIN HARDENING COEFFICIENT VS α_A

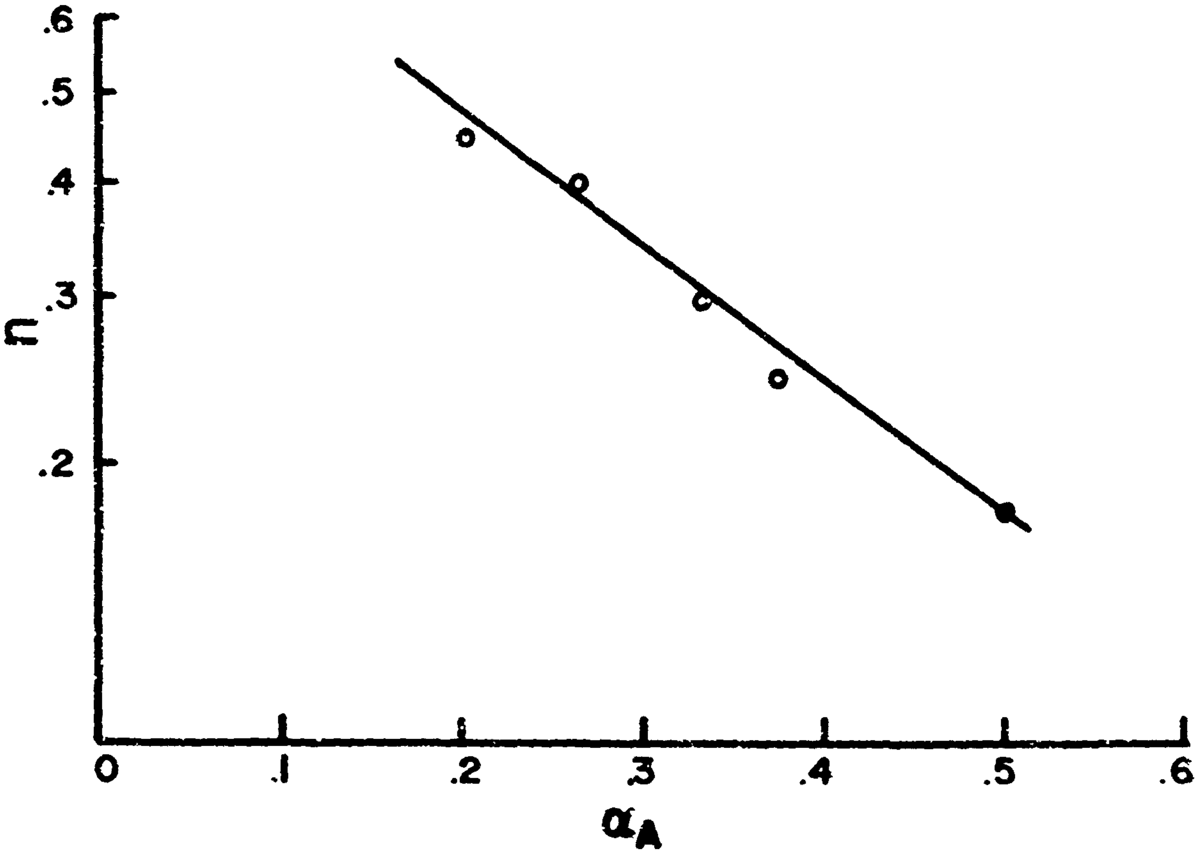

Figure 6. n vs. α_A $\quad \alpha_A = \epsilon_\beta / \epsilon_{pl}^{\frac{1}{2}}$

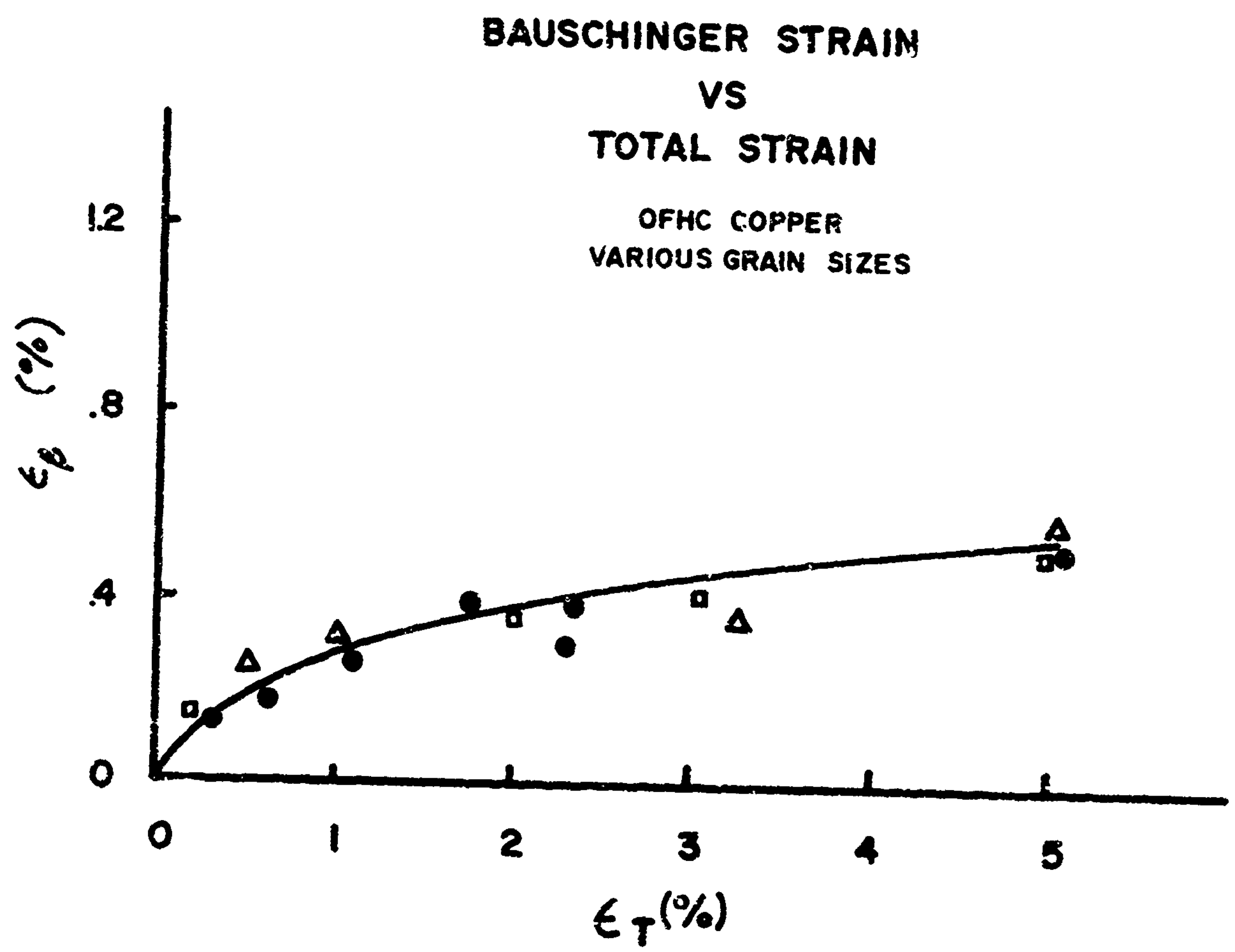

Figure 7a. ϵ_β vs. ϵ_{total} OFHC Cu - 3 Different Grain Sizes

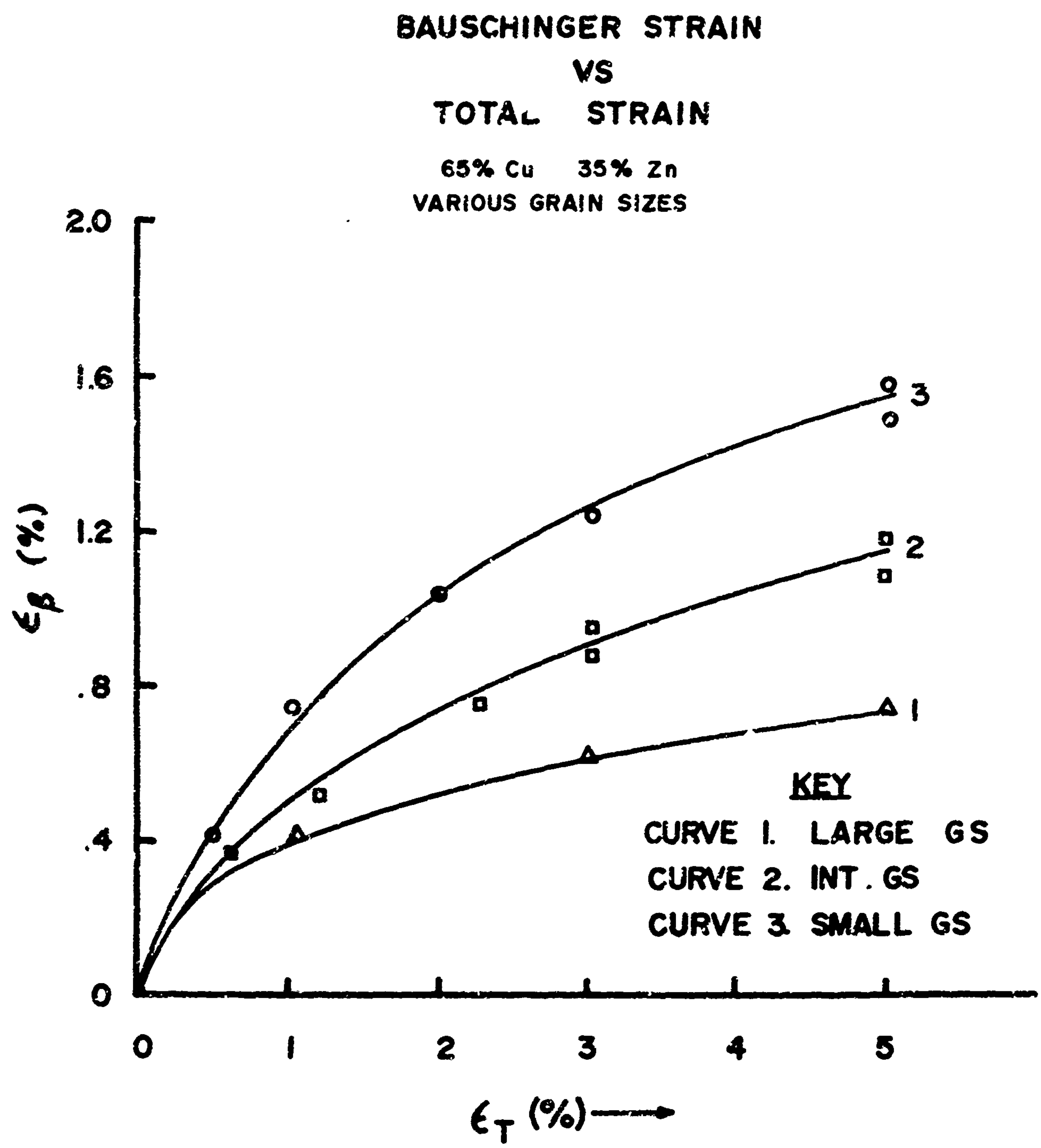

Figure 7b. ϵ_β vs. ϵ_{total} 65/35 Brass - 3 Different Grain Sizes

effect is apparently independent of grain size in the pure metal but depends on grain size in the alloy. A possible explanation is that cross slip is able to take place in the copper so the dislocations move in many planes causing dislocation interaction, hence making it difficult for them to move back once the direction of loading has been reversed. On the other hand, in brass, the dislocations are more constrained to move in a plane and it is much easier for them to move back in compression giving rise to a larger BE.

These results confirm Woolley's conclusion for the pure metals but is in opposition to his general statement of the BE being independent of grain size as far as one of the alloys investigated in this study is concerned.

CONCLUSIONS

1. The Bauschinger effect strongly depends on the alloy composition for the copper and brass alloys studied.

2. The Bauschinger strain is a function of the plastic strain to the one half power for each of the alloys investigated for tensile strains up to 5 percent.

3. Preliminary data shows that the BE is independent of grain size for copper, whereas the 65% Cu 35% Zn alloy shows a grain size dependence.

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13. ABSTRACT

A series of five different copper-zinc polycrystalline alloys, ranging from commercially pure copper to 65% Cu 35% Zn brass, were strained various amounts up to 5% in tension and reverse strained in compression. The Bauschinger strain is shown to be dependent on composition. An equation relating plastic strain and the Bauschinger effect is presented and experimentally verified. Preliminary data shows that the Bauschinger strain is dependent on grain size for the 65% Cu 35% Zn alloy, but is independent of grain size for the OFHC copper.

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